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Corn yield and nitrogen recovery following rye (*Secale cereale* L.) in monoculture and polyculture service crops

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Abstract

Planting service crops (SCs) with late summer manure applications has been promoted as an agronomic practice to capture manure nitrogen (N) and release it to the following season's cash crop, thereby reducing fertilizer N requirements. The present study explored this hypothesis using a cereal rye (*Secale cereale* L.) monoculture SC, along with two polyculture SCs (4 species and 12 species) both containing rye, planted after winter wheat (*Triticum aestivum* L.) harvest, in systems with and without liquid hog manure. The following spring, SC regrowth was chemically terminated 1 week prior to corn (*Zea mays* L.) planting, and a sidedress N application was made at the 6–8 leaf stage to half of the plots. Corn N accumulation and final grain yield were reduced up to 20% following the rye monoculture in both years, even though SCs did not reduce soil mineral N nor partial plant-available N over the corn-growing season. Additionally, the sidedress N application could not overcome the yield loss associated with rye. Thus, this study did not observe N release by SCs to the following cash crop and demonstrates that yield loss can occur when corn follows rye SCs irrespective of changes in plant available N. This research reinforces the importance of selecting appropriate species and their proportions in polycultures, to mitigate negative impacts of SCs, especially those of rye on corn.

Key words: cover crops, cereal rye, polycultures, manure, corn, nitrogen

Résumé

Planter une culture-abri et épandre du fumier à la fin de l'été sont vantés comme de bonnes pratiques agronomiques pour capter l'azote (N) que renferment les déjections animales et le libérer la saison suivante de manière à réduire les besoins en engrais azotés. Les auteurs ont vérifié cette hypothèse en utilisant comme culture-abri du seigle (Secale cereale L.) ou deux polycultures (quatre espèces et douze espèces) incluant chacune du seigle, toutes semées après la récolte du blé d'hiver (Triticum aestivum L.), avec ou sans épandage de lisier de porc. Le printemps suivant, ils ont mis fin à la culture-abri par traitement chimique une semaine avant la plantation du maïs (Zea mays L.). La moitié des parcelles ont reçu une application latérale d'engrais N au stade de la sixième-huitième feuille. L'accumulation de N dans le maïs et le rendement grainier final ont baissé de 20 % après la monoculture de seigle, les deux années, bien que la culture-abri n'ait pas réduit la concentration de N minéral dans le sol, ni la proportion du N assimilable par la plante pendant la période végétative. D'autre part, l'application latérale de N n'a pas compensé la baisse de rendement attribuable au seigle. Les auteurs en concluent que la culture-abri n'a pas libéré de N que la culture commerciale aurait pu assimiler l'année suivante. En revanche, le rendement du maïs peut diminuer après la culture-abri, peu importe la variation de la quantité de N à la disposition de la plante. Les résultats de ces travaux montrent que si on veut atténuer les effets négatifs des cultures-abris, celle de seigle surtout, sur le maïs, il importe de choisir les bonnes espèces et leurs proportions dans une polyculture. [Traduit par la Rédaction]

Mots-clés : culture-abri, seigle, polycultures, fumier, maïs, azote

Introduction

Managing manure nitrogen (N) applied in summer is a challenge for crop–livestock farmers. Nitrate leaching, ammonia volatilization, and denitrification over the nongrowing season all have significant environmental externalities, in addition to the loss of fertilizer replacement value from manure. Service crops (SCs; commonly known as cover crops) are plants grown for the ecosystem services they provide, rather than a harvestable product (Ogilvie et al. 2019). It is well established that SCs can successfully recover leachable N (Vyn et al. 2000; Parkin et al. 2006; Krueger et al. 2011; Thilakarathna et al. 2015; Komainda et al. 2018). However, it is not clear that SCs will reliably release manure N to synchronize with the N demand of subsequent corn (*Zea mays* L.) growth.

Species selection and biomass quantity and quality of SCs strongly influence N release patterns from SCs (Wagger et al. 1998; Dabney et al. 2001). For example, following fall termination, timing of N release from red clover (*Trifolium pratense* L.) interseeded into winter wheat (*Triticum aestivum* L.) is understood to synchronize well with corn N demand in northern temperate agroecosystems (Vyn et al. 2000; Gaudin et al. 2013; Thilakarathna et al. 2015). Indeed, corn yields tend to respond positively to prior leguminous SCs (Kramberger et al. 2009; Marcillo and Miguez 2017).

The same cannot be said for some cereals like cereal rye (*Secale cereale* L.; hereafter referred to as rye) (Martinez-Feria et al. 2016). For example, Thilakarathna et al. (2015) did not find evidence that perennial ryegrass (*Lolium perenne* L.) nor oat (*Avena sativa* L.) transferred N from fall-applied liquid hog manure to the following corn crop, though red clover had positive fertilizer-N equivalent and apparent N recovery values. Similarly, Seman-Varner et al. (2017) reported an N credit to corn when poultry litter was fall-applied in combination with a legume SC (crimson clover [*Trifolium incarnatum* L.] or hairy vetch [*Vicia villosa* Roth]), but there was no N credit from rye. Raimbult et al. (1991) and Tollenaar et al. (1993) observed reductions in corn yields after rye, possibly caused by allelopathic or phytotoxic exudates from rye. However, tests of extracts from three rye populations, in other research did not reveal an allelopathic effect on corn (Dhima et al. 2006).

Service crop polycultures may provide intermediate levels of N recovery and release along with other ecosystem services (Finney and Kaye 2017; Thapa et al. 2018; Ogilvie et al. 2019). A study by Hunter et al. (2019) found that comparable corn yields were achieved following polycultures with low C:N, as with legume monocultures. The meta-analysis by Marcillo and Miguez (2017) reported a 13% average increase in corn yields following SC polycultures, compared with a 21% increase following legume SCs, and no change following grasses, in systems where fertilizer N is not adjusted for SC N contributions. More research is needed to explore manure N recovery and release from SC polycultures, especially those including rye, relative to monocultures and the subsequent effect on corn yield and N uptake. The objectives of this study were to determine the effect of a rye monoculture and two polyculture SCs, which included rye, with and without manure, on corn yield and apparent N recovery.

Materials and methods

Site description

The experiment was established on two neighboring fields in the summers of 2016 and 2017 on a commercial farm (42°33′57″N, 82°10′23″W) near Dresden, ON. The soils at the site are listed as mainly the Tavistock and Maplewood soil series with complex slopes and some Bennington series at the crests of slopes (AAFC 2000). The soil is imperfectly (Maplewood) to poorly drained (Tavistock), depending on landscape position; both fields had been tile drained as is typical for the region. Based on the analysis of seven samples, the texture (the hydrometer method) at the site was found to be a sandy loam with 55% sand, 28% silt, and 17% clay on the first field (2016–2017), and a loam with 30% sand, 47% silt, and 23% clay on the second field (2017–2018). The first field had a soil pH of 6.1, organic matter (Walkley–Black) of 3.4%, and phosphorus (sodium bicarb) of 19 ppm; the second field had a pH of 5.9, organic matter of 4.1%, and phosphorus of 46 ppm. Both fields had been in a corn–sugar beet (*Beta vulgaris* subsp. *Vulgaris* L.)–soybean (*Glycine max* L. Merr.)–winter wheat rotation with strip-tillage, manure, and SCs for approximately two cycles and a long history of liquid swine manure applications.

Experimental design

The experimental design was a three-factor factorial in a split block-by-split plot arrangement: SCs (no service crop (noSC), monoculture rye, four-species polyculture,12-species polyculture; Table 1) were the main plot factor, manure was applied or not applied in a split block fashion perpendicular to the SC plots, and sidedress-N was applied or not applied in a split plot fashion within each SC plot. In both fields, this was replicated four times for a total of 64 plots that were ∼30 m long by 3 m wide to allow for commercial equipment and multiple destructive samples to be taken over the course of the season.

Site management

The experimental sites were established after winter wheat harvest; straw and chaff were chopped with John Deere's 9660 stock residue sizing and distribution system and spread across the field. In late July (Table 2), ∼70 000 L ha^{-1} of liquid hog manure was applied to the manure split of each block with a Kuhn liquid manure injector at approximately a 5-cm depth with discs spaced 28 cm apart; manure was applied in a path perpendicular to the planting of SCs and corn. Before filling the tanker, the manure pit had been agitated for approximately 1 h; manure samples for nutrient analysis were taken from the flow stream as the tanker was being filled (analysis was conducted by A&L Canada Laboratories Inc., London, Ontario). In year 1, manure composition was 2.7% dry matter, 0.1022% total phosphorus, 0.3353% total potassium, 0.622% total N, and 5319 ppm NH_4-N; thus, about 435 and 372 kg ha^{-1} of total and NH_4-N applied, respectively. In year 2, the manure was similar with 2.7% dry matter, 0.1053% total phosphorus, 0.3625% total potassium, although total N was lower at 0.427% and 3492 ppm NH_4-N; thus, about 299 and 244 kg ha^{-1} of total and NH_4-N applied, respectively.

SCs were planted within 2 days of manure application with a 3 m John Deere seed drill set at 19 cm row spacing. Volunteer wheat in the noSC control was terminated with glyphosate at 2.47 L ha^{-1} (1186 g a.e. ha^{-1}) late-September. All plots were strip-tilled early-November in 2016 and 2017 with an Orthman 1tRIPr strip till unit outfitted with a shank, containment coulters, and rolling basket harrows at 76 cm centers, creating a ∼25 cm strip. The following spring, regrowing SCs were terminated 1 week before corn planting with glyphosate at 3.3 L ha^{-1} (1380 g a.e. ha^{-1}) tank-mixed with saflufenacil at 71 g a.i. ha^{-1} in 2017, and with 3.3 L ha^{-1} glyphosate alone in 2018. Pioneer P0474 and P0414 corn

Table 1. Service crop treatments descriptions.

Treatment	Species	Planting rate (kg ha^{-1})
noSC	–	–
Rye	*Secale cereale*	28.0
4sp	*Secale cereale*	28.0
	Trifolium incarnatum	5.6
	Echinochloa esculenta	1.1
	Helianthus annuus	2.2
12sp	*Secale cereale*	16.8
	Trifolium incarnatum	5.6
	Echinochloa esculenta	1.1
	Helianthus annuus	2.2
	Brassica rapa subsp. *rapa*	0.1
	Brassica oleracea	0.1
	Avena sativa	9.0
	Vicia villosa	2.2
	Trifolium repens	1.1
	Pisum sativium subsp. *Arvense*	13.5
	Fagopyrum esculentum	3.4
	Sorghum bicolor x Sorghum bicolor var. *Sudanese*	3.4

Abbreviations: noSC, no service crop; Rye, one species; 4sp, four species; 12sp, twelve species.
Note: Seeds were acquired through Quality Seeds Ltd. (Vaughan, ON) except for *H. annuus*, *B. rapa* subsp. *rapa*, *A. sativa*, and *S. cereale*, which were bin-run seeds sourced from a local feed mill.

Table 2. Timing of site management and sampling activities over the course of the experiment.

Activity	Field 1	Field 2
	2016	2017
Winter wheat harvest	13 July	19 July
Manure applied	24 July	24 July
Service crops planted	25 July	26 July
Service crop height measurements taken	9 September	8 September
Volunteer wheat chemically terminated in noSC	26 September	25 September
Service crop fall biomass sampled	24–25 October	19–21 October
Strip tillage performed	8 November	12 November
	2017	2018
Service crop spring residue and soil sampled	13 April	23 April
Service crop chemically terminated	22 April	24 April
Corn planted	29 April	1 May
Sidedress UAN applied	16 June	14 June
Corn and soil sampled	28 June	28 June
Corn and soil sampled	29 August–1 September	20 August
Accumulated > 3125 CHUs (i.e., physiological maturity)	23 September	7 September
Corn harvested and soil sampled	26–30 October	3–4 October

Abbreviations: noSC, no service crop; UAN, urea ammonium nitrate; CHU, crop heat units.

(both 104-day maturity corn cultivars) were seeded in 2017 and 2018, respectively, at a target population of 74 600 plants ha^{-1}, with 76 cm row spacing and no starter fertilizer. The side-dress (SD) treatment was urea–ammonium nitrate (28–0–0) application was injected between the corn rows in June at the 6–8 leaf stage (the collar method) at 468 L ha^{-1} (168 kg N ha^{-1}).

Weather

Hourly temperature and rainfall were monitored with an ADCON (Austria, Europe) weather station. The months of July–August of 2016 were as much as 4 °C warmer and had more than double the amount of rain than either the 30-year monthly average or the corresponding period in 2017 (Table 3). The overwintering periods were also differ-

Table 3. Weather data from July 2016 to October 2018 at VanArkel farm and 30-year means from Dresden, ON

	Mean temperature (°C)				Total precipitation (mm)			
Month	2016	2017	2018	30-year*	2016	2017	2018	30-year*
Jan	–	− 1.0	− 5.4	− 5.5	–	35.0	35.0	51.5
Feb	–	1.6	− 2.0	− 4.4	–	60.6	62.6	48.5
Mar	–	1.2	− 0.2	0.7	–	98.4	39.0	55.4
Apr	–	10.6	3.9	7.3	–	74.8	76.4	79.5
May	–	13.6	17.3	13.9	–	133.8	64.0	76.5
June	–	19.8	20.0	19.1	–	69.6	100.2	90.2
July	23.0	21.6	21.7	21.4	137.2	38.4	39.6	80.4
Aug	23.3	19.3	22.1	20.3	184.2	69.2	133.4	80.2
Sept	19.2	17.0	19.0	16	97.6	47.2	45.0	107.5
Oct	12.4	12.8	10.1	10	54.8	75.0	116.6	68.7
Nov	7.0	3.7	–	3.5	43.6	113.2	–	84.8
Dec	− 1.7	− 4.6	–	− 1.7	42.4	18.0	–	65.6

*Historical weather data gathered from the Canadian Climate Normals database for Dresden, ON (1981–2010), approximately 2 km from the experimental site. En dashes ("–") are used where weather data were outside of the timeline of the experiment.

ent with January–March 2017 being up to 6 °C warmer than the historical monthly average, whereas the same period in 2018 was not different than historical averages. In the 2 weeks after planting in 2017, the average daily temperature was 9.4 °C and 89.6 mm of rainfall had accumulated; water ponding was observed as evidenced by soil surface crusting and movement of crop residues. Moderate-to-severe slug damage was observed throughout the field, consistent with other province-wide observations (Baute 2017). For the same period in 2018, the average daily temperature was 14.7 °C and 45.2 mm of rainfall had accumulated (30-year [1981–2010] average rainfall for the month of May is 76.5 mm). The 2017 and 2018 corn-growing seasons were similar to historical average temperatures for the area. Rainfall from June to September in 2017 was 230 mm, whereas in 2018 and historically, it was 435 and 427 mm, respectively.

Service crop, soil, and corn sampling

Service crop fall above-ground biomass was harvested from four 0.5 m^2 quadrats per plot. With the polyculture treatments, species were sorted and weighed separately. Species proportions in the polycultures were calculated using biomass from all four 0.5 m^2 quadrats combined. Biomass was dried at 65 °C, and dry weights were recorded for each species and quadrat. The four quadrats were combined into one sample per plot for C and N analysis; these were then shredded using a gas-powered chipper shredder, and subsamples were ground to pass through a 2-mm sieve using a Wiley mill (Thomas Scientific, Swedesboro, NJ, USA). In the spring, SC residue was sampled prior to corn planting from four 0.5 m^2 quadrats per plot placed between the tilled strips; SC regrowth (mostly rye) was not separated from dead residue but was included in the total sample weight. Samples were dried at 80 °C, and dry weights were recorded for each quadrat. Nutrient content was not determined for spring residue.

Soil samples were collected at four times (Table 2). Prior to corn planting, ten 2 cm diameter × 30 cm deep cores were collected systematically across the plot, both in and out of the tilled strips; in June and August, five cores were taken 20 cm from the corn row (to avoid fertilizer bands) in the area used for destructive corn sampling (see below); and at corn harvest, ten cores were taken 20 cm from the corn row in the harvested area. At each of these times, soil was homogenized to form one composite sample per plot and then frozen until mineral N analysis.

Aboveground corn biomass was sampled in June (six to eight leaf stage) and August (silking) (Table 2) by harvesting ten neighboring corn plants from the same row and measuring the length of the harvested area. Samples were dried at 65 °C, and dry weights were recorded. The samples were then shredded using a gas-powered chipper shredder, and subsamples were ground to 2 mm using a Wiley mill (Thomas Scientific, Swedesboro, NJ, USA) to prepare for C and N analysis.

Corn harvest population was determined by counting the number of plants within two neighboring, representative, well-bordered 10 m rows, for a total harvest area of 15.2 m^2. Cobs from 40 plants within the 15.2 m^2 harvest area were systematically selected, weighed fresh, dried at 65 °C, shelled, and grain was weighed dry. The stover of the corresponding 40 plants was cut 3 cm above ground level, weighed fresh, and a subsample of eight plant stover was weighed fresh, dried at 65 °C, and weighed dry (including the shelled cob). Moisture contents of the cobs and plant stover from the 40-plant subsample were used to approximate grain and stover dry weight of the total 15.2 m^2 harvest area. The remaining cobs and plant stover in the harvest area were collected, weighed fresh, and discarded. Corn grain yields are reported at 15% moisture.

Soil and plant nutrient content determination

Soil ammonium and nitrate N was extracted with 2 mol KCl (Maynard et al. 2008) and analyzed with a continuous segmented flow autoanalyzer (SEAL Analytical AutoAnalyzer III; Mequon, WI), using cadmium reduction and salicylate–dichloroisocyanuric acid procedures for NO_3 and NH_4, respectively. Soil mineral N concentrations (mg kg^{-1}) were converted to kg N ha^{-1} based on the bulk density of soil samples taken from the site at the 5–10 cm depth (between 1.27 to 1.39 g cm^{-3}). SC and corn N concentrations were analyzed using a LECO TruSpec CN Carbon Nitrogen Determinator (LECO Corporation, St Joseph, MI) by combustion of a 0.1 g subsample of SC biomass, corn biomass, or corn grain. Partial plant available N—not including root N accumulation—for corn was calculated by summing the soil, grain, and stover N contents.

Statistical analysis

Statistical analyses were conducted in SAS 9.4 (SAS Institute Inc., Carey, NC). Analysis of variance (ANOVA) was performed using the GLIMMIX procedure at a Type I error rate of 0.05. The experimental year was treated as a fixed effect along with manure, SC, and SD. Random effects included block, year(block); in cases where subsamples were taken, or where multiple samples were taken over time, random effects were adjusted to account for multiple sampling. For example, SC biomass and residue were analyzed according to a split block design with multiple samples; SC N content, and soil mineral N at planting were analyzed according to a split block design; soil and corn N content were analyzed according to a repeated-measures, split block-by-split plot design; and final corn yield was analyzed according to a split block-by-split plot design.

Plots of residuals were checked to ensure that errors fit model assumptions; where there was heterogeneity of error, the data were either transformed or modifications to G-side or R-side covariance structure were made. When a lognormal distribution was used, least-squared means on the data scale were calculated using the delta method (Bowley 2015). Preplanned orthogonal contrasts were used when appropriate to make pooled comparisons between the SC treatments and the noSC control. In all cases, the Kenward–Rogers adjustment was applied to correct for degrees of freedom and means comparisons were made using the Tukey–Kramer adjustment at $\alpha = 0.05$. Means comparisons among main effects were not explored where there were significant interactions. Where there were significant interactions with year, data were sliced to explore treatment pairwise comparisons in each year.

Results

Service crop fall biomass and nitrogen, and spring residue

In both years, adding manure to a rye SC nearly doubled the amount of fall biomass compared with no-manure (Fig. 1). But only in fall 2016 did manure increase the total biomass of the 4sp and 12sp SC polycultures. While seeding rates were the same in both years, the proportions of species biomass in the polycultures were different from 2016 to 2017. In fall 2016 with manure, there was 326 and 956 kg ha^{-1} rye biomass in the 12sp and 4sp polycultures, respectively, compared with 2981 kg ha^{-1} rye biomass in the monoculture (Fig. 1). Millet in 4sp and 12sp responded to manure leading the polycultures to produce 3–4 t ha^{-1} more total biomass than the monoculture in fall 2016, while also significantly increasing their biomass relative to no-manure.

In 2017, rye dominated the polycultures such that there was no difference in rye biomass between the polycultures and the monoculture, with or without manure. There was also no difference in total polyculture biomass, or rye biomass in the polycultures, between manure and no-manure; and with manure, there was no difference in total biomass between rye or the two polycultures (Fig. 1). In the two polycultures, millet made up only 0%–4% of total biomass in 2017 compared with 19%–24% in 2016; and sorghum comprised only 2% of the total 12sp biomass in 2017 compared with almost 20% in 2016. Legume contents were negligible in both years.

Averaged across both years, fall above-ground biomass N accumulation differed among SCs ($P = 0.0029$) such that the 4sp and 12sp polycultures accumulated 88.1 and 94 kg N ha^{-1}, respectively, whereas the rye monoculture accumulated 66.2 kg N ha^{-1} (Fig. 2). There were no SC interactions for fall biomass N accumulation. SCs responded to manure in both years ($P = 0.0195$) and accumulated 120.8 and 128.5 kg N ha^{-1} with manure versus 41.8 and 69.2 kg N ha^{-1} without manure, in 2016 and 2017, respectively (Fig. 3). The SC C:N ratio also responded to manure ($P = 0.0192$) being 19.7 without manure and 16.0 with manure. The year × SC interaction was also significant ($P = 0.0009$) such that in 2016 C:N ratios increased from rye to 4sp to 12sp, but there were no differences in 2017 (Table 4).

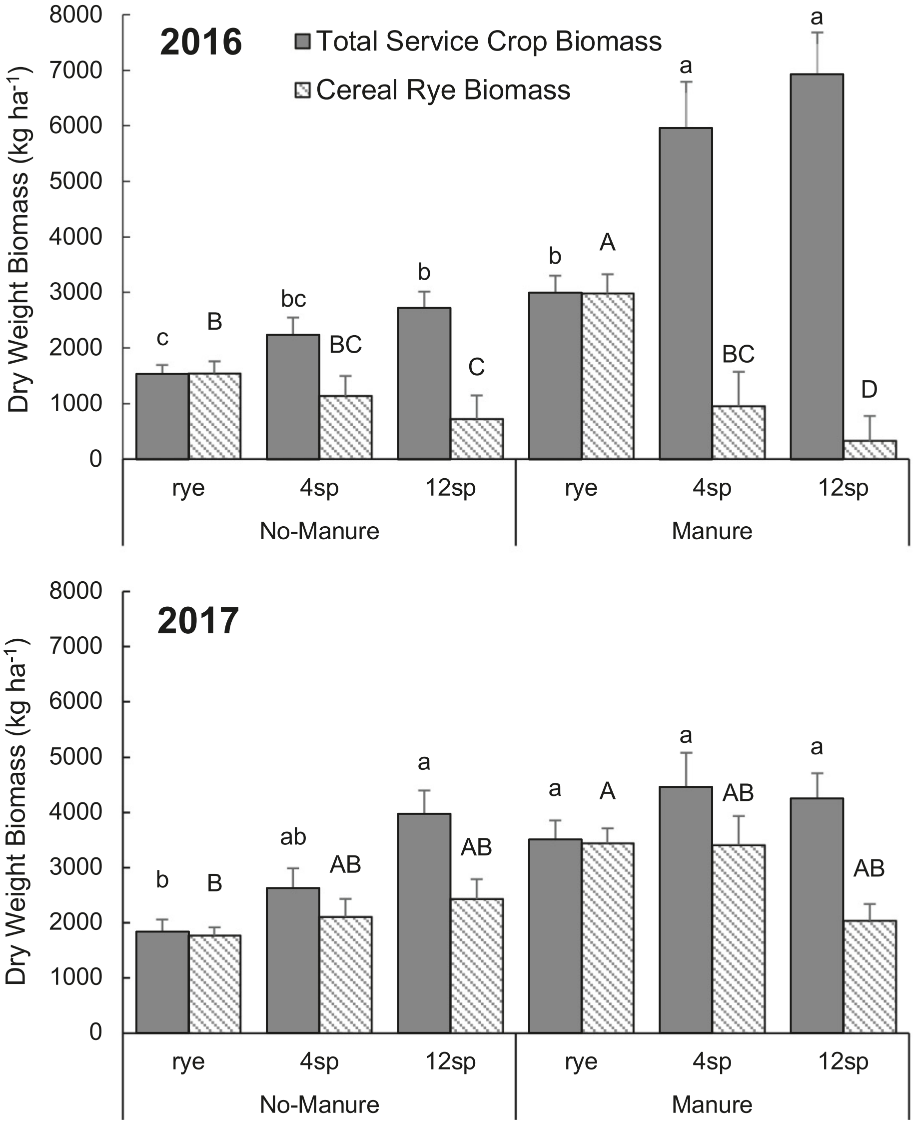
The following spring at corn planting, there were no differences in the amount of residue (dead residue and regrowth combined) among the treatments due to either SCs or manure. There was approximately 4 Mg ha^{-1} of straw residue across the treatments.

Soil and corn nitrogen over the growing season

In April 2017, soil mineral N in the surface 30 cm depth ranged from 23.4 to 34 kg N ha^{-1}; in April 2018, soil mineral N ranged from 73.2 to 118.9 kg N ha^{-1}, where the period around planting was warmer and drier than in 2017. While there was a significant year × manure × SC interaction at corn planting ($P = 0.0229$), there were no major differences in soil mineral N levels among SC or manure treatments in April 2017 or 2018 (data not shown). There were also no differences in soil mineral N across SC treatments from June through October in either year ($P = 0.131$).

Corn shoot N accumulation was affected by SCs ($P = 0.0279$) such that shoot N content was reduced following rye compared with noSC, averaged over both years (Table 5). However, there were no SC × manure ($P = 0.5863$), SC × SD ($P = 0.7497$) or SC × sampling date ($P = 0.4315$) interactions in corn shoot N content over the June and August sampling dates. Corn C:N over the same period was not different between SC treatments ($P = 0.2592$) and neither was % N ($P = 0.4228$), suggesting that corn response to SC was independent of soil N.

Fig. 1. Total SC fall biomass and the amount of cereal rye biomass within the three SC treatments, under no-manure or manure, from October 2016 and 2017. (a–c/A–D) Different letters with the same case indicate statistical difference according to Tukey–Kramer adjust means comparisons at $\alpha = 0.05$. Abbreviations: rye, cereal rye monoculture, 4sp/12sp, four/twelve species polyculture. In both years across treatments, cereal rye biomass includes volunteer wheat given that it was not separated from cereal rye biomass.



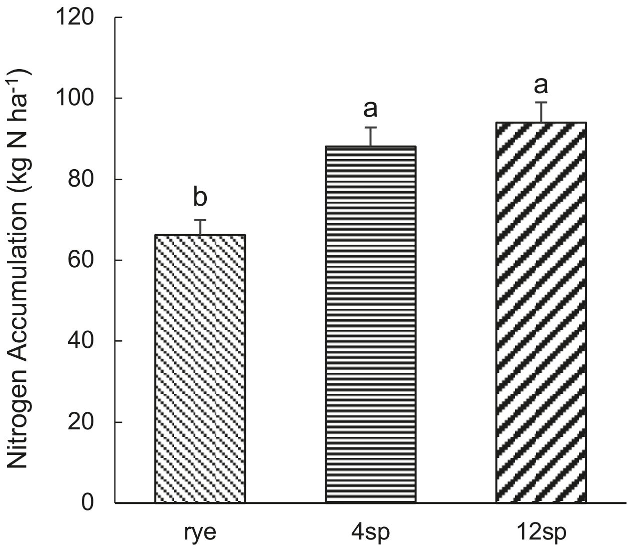
Corn yield and nitrogen at harvest

In 2017, there were no differences in corn harvest population, which was 6.75 plants m^{-2}; but in 2018, harvest population was significantly reduced ($P = 0.0046$) in all SC treatments (7.73, 7.35, and 7.23 plants m^{-2} for rye, 4sp, and 12sp, respectively) compared with noSC at 8.61 plants m^{-2}.

Without manure, there was no SC effect on corn grain yield in either year (Fig. 4). But with manure, 2017 grain yield following rye was significantly less than noSC or 12sp, which had small amounts of rye. Grain yield was reduced following rye in 2018 compared with noSC, but there were no differences among the other treatments. Grain N accumulation was also significantly reduced following rye (106 kg N ha^{-1}), and was not different between noSC, 4sp, or 12sp (138, 122, and 125 kg N ha^{-1}), respectively (Table 6).

Averaged over the 2 years, total corn biomass at harvest was reduced following rye compared with noSC, and biomass following 4sp and 12sp were intermediate but not different from noSC or rye (Table 7). Corn stover N accumulation following rye (68 kg N ha^{-1}) was also reduced compared with noSC (78 kg N ha^{-1}), and stover N following 4sp or 12sp (71 or 72 kg N ha^{-1}, respectively) was not different from either noSC or rye (Table 6). There was no effect of SCs on stover C:N at harvest ($P = 0.9373$). Finally, there was no significant effect of SCs or any SC interaction on partial plant-available N over the entire corn-growing season.

Fig. 2. Fall SC biomass nitrogen accumulation, averaged across 2016–2017 and manure treatments. (a–b) Different letters indicate statistical difference according to Tukey–Kramer adjust means comparisons at $\alpha = 0.05$. Abbreviations: rye, cereal rye monoculture; 4sp/12sp, four/twelve species polyculture.



Discussion

Variability in service crop growth

This experiment set out to evaluate the ability of SCs to capture manure N and release it to a subsequent corn crop. SCs were able to capture manure N in the fall (Figs 2–3), but overall biomass production was variable (Fig. 1). The challenge of one or a few species dominating, outcompeting, or even antagonizing the others within SC polycultures has been observed in other research, especially with cereal rye (Bugg et al. 1991; Anderson 2016; Finney et al. 2016; Appelgate et al. 2017; Murrell et al. 2017). This result was observed in the present study where the SC polycultures had different species biomass proportions across the 2 years they were grown. Higher temperatures, more rainfall, deeper seed placement at planting, or even higher N-content of the manure may have contributed to the greater success of millet and sorghum in 2016 than 2017. In the end, cereal rye dominated the fall biomass in the 4sp and 12sp polycultures in 2017 such that there was no difference in the amount of rye biomass between the monoculture and the two polycultures (Fig. 1). The variability in SC growth appears to be the source of differences in corn growth and productivity the following season.

Impacts of cereal rye on corn production

While SCs responded to manure in both years, there was no detected increase in plant available N due to SCs the following season. This suggests that, if SCs can recover and release manure N to the following season's cash crop, it does not occur at the same time as corn N demand. Other research similarly shows that the impact of nonlegume, summer-seeded SCs on soil N levels the following season is limited (Pantoja et al. 2015; Ruark et al. 2018; Rutan and Steinke 2019).

Instead of improving corn production the following season, corn following the rye monoculture performed poorly, having lower populations compared with the control in 2018, reduced N accumulation over the June–August period (Table 5), reduced grain (Fig. 4) and total biomass yield (Table 7), and reduced grain and stover N content (Table 6). Vyn et al. (2000) found that yield differences in corn following SCs did not exist when in-season fertilizer N was added, suggesting immobilization due to the SCs. This was not observed in the present experiment. The SD application increased N uptake and grain yields in all treatments, but the added fertility did not overcome the negative effect of rye; notably there were no interactions between SD and SC. Furthermore, the ~20% lower yield of the rye treatment, compared with the noSC treatment, only occurred when manure was applied (Fig. 4); this coincided with the increase in rye biomass from adding manure. In both years, there was no statistical difference in corn yield between the SC treatments and the control when no manure was applied; adding manure doubled the monoculture rye biomass from the previous fall (Fig. 1) and resulted in lower grain yields following rye compared with noSC. In contrast, adding manure decreased the proportion of rye biomass in 4sp and 12sp in fall 2016 by ~70% and 90%, respectively; and 2017 grain yield following these polycultures was not different than the control.

Several lines of evidence suggest that the negative effect of rye on corn was not N-related. First, soil mineral N levels at planting were nonlimiting and there were no differences between SC in either year. Second, there was no reduction in soil mineral N levels due to SCs over the June–October period. Third, while corn N accumulation was reduced following rye compared with noSC (Table 5), this is explained by the reduction in overall biomass, since there were no differences in corn C: N between SCs. Finally, there was no effect of SCs on partial plant-available N across either growing season. Corn plants following rye were less effective in accumulating available N. Collectively, these results run contrary to the hypothesis that SCs would increase plant available N from manure the following season, but they also stand in contrast to a number of studies where the cause of reduced corn yield following rye was attributable to reduced N availability (Tollenaar et al. 1993; Vyn et al. 2000; Appelgate et al. 2017). In the present study, a reduction in corn yield was observed irrespective of plant-available N.

There are alternative mechanisms that can explain lower biomass production, yield, and N accumulation following rye. Martinez-Feria et al. (2016) reported significant reductions in corn grain yield (14%–34%), following cereal rye in 2 years of their experiment when conditions were dry. Munawar et al. (1990) also connected reduced corn yields following rye to dry conditions, and Krueger et al. (2011) demonstrated water depletion by a rye SC—though this did not reduce corn yields. Using the same experimental plots as the present study, a related study on water dynamics did not find that the rye SC depleted soil–water relative to noSC (Ogilvie 2019). In the temperate region where this study was conducted, spring rains

Fig. 3. Fall service crop nitrogen accumulation separated by year and manure application. (a–c) Different letters indicate statistical difference according to Tukey–Kramer adjust means comparisons at $\alpha = 0.05$.

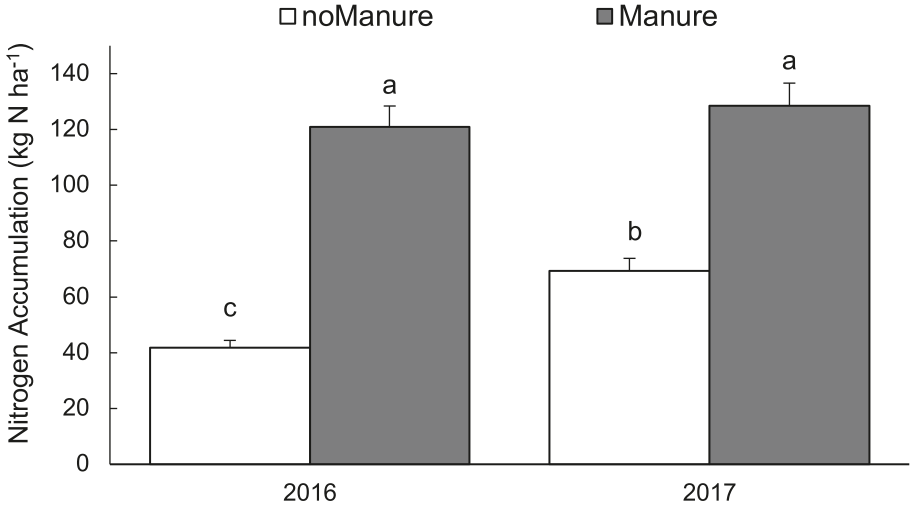


Table 4. Service crop fall C: N in 2016 and 2017.

	SC	C:N	SE
2016	rye	16.2c	1.0
	4sp	21.7b	1.0
	12sp	25.1a	1.0
2017	rye	14.3c	1.1
	4sp	14.5c	1.0
	12sp	15.6c	1.0

(a–c) Different letters within a column indicate statistical difference according to Tukey–Kramer adjust means comparisons at $\alpha = 0.05$.
Abbreviations: SC, service crop; rye, cereal rye monoculture; 4sp/12sp, four/twelve species polyculture; SE, standard error.
Note: Other interactions with manure were not statistically significant.

Table 5. Corn shoot N accumulation over the June–August sampling times by the SC main effect, averaged across years, manure treatments, and SD.

SC	kg N ha^{-1}	SE
noSC	83a	6
rye	66b	5
4sp	69ab	5
12sp	68ab	5

(a–b) Different letters within a column indicate statistical difference according to Tukey–Kramer adjust means comparisons at $\alpha = 0.05$.
Abbreviations: SC, service crop; rye, cereal rye monoculture; 4sp/12sp, four/twelve species polyculture; SD, sidedress; SE standard error.
Note: SC main effect is averaged over manure, SD, sampling times, and experimental years since other main effects and (or) interactions were not statistically significant.

are often sufficient to replenish soil water reserves (Unger and Vigil 1998; Basche et al. 2016).

Some research has also suggested that reductions in corn yield are caused by allelopathic or phytotoxic exudates from rye (Raimbult et al. 1991; Tollenaar et al. 1993). However, Dhima et al. (2006) tested extracts from three rye populations and did not find an allelopathic effect on corn—though there were allelopathic effects on other grass species. Duiker and Curran (2005) did not detect any allelopathic effect of rye on corn populations or yield in either zone-till or no-till treatments, similar to the system in the present study, and Kaspar and Bakker (2015) found that negative effects on corn populations and yield (not necessarily allelopathic) depended on the rye cultivar. In contrast to corn, soybean yields usually increase following a rye cover crop (Beach et al. 2018), implying that, unlike corn, soybean yield is not negatively affected by rye.

Bakker et al. (2016) saw an increased prevalence of root rot diseases in corn planted after a rye SC. Additionally, Acharya et al. (2017) demonstrated that when corn was planted less than 10 days after rye termination in a no-till system, corn grain yield was reduced compared with corn planted more than 10 days after termination, or corn following noSC. Further study indicated that *Pythium* spp. were largely responsible for this disease complex, and that fungicide treatments targeting *Pythium* spp. were able to reduce disease incidence (Acharya et al. 2018). In-field effects of rye before corn included reduced populations, yield, and yield-per-plant at harvest (Acharya et al. 2018).

Researchers in the present study were unaware of the recommendation of Acharya et al. (2017) to plant corn more than 10 days after rye termination; corn was planted 7 days after terminating SCs, in both years. Reductions in corn N accumulation and yield, following rye, could have been due to pathogen transfer from rye to corn. The manure application prior to SC planting, coupled with warmer weather and more rainfall, likely favored the growth of warm-season grasses in year 1, leading to a significant decrease in rye biomass in the two polycultures while increasing rye biomass in the rye monoculture (Fig. 1). This presumably created a larger root system and a more dispersed host habitat for root pathogens throughout the soil (Acharya et al. 2017). In the present study, given that rye regrowth was terminated only 7 days prior to planting, and with a planter setting of insufficient coulter force to cut any rye roots extending to the corn strip, it is possible that rye roots could still have had active tissue as

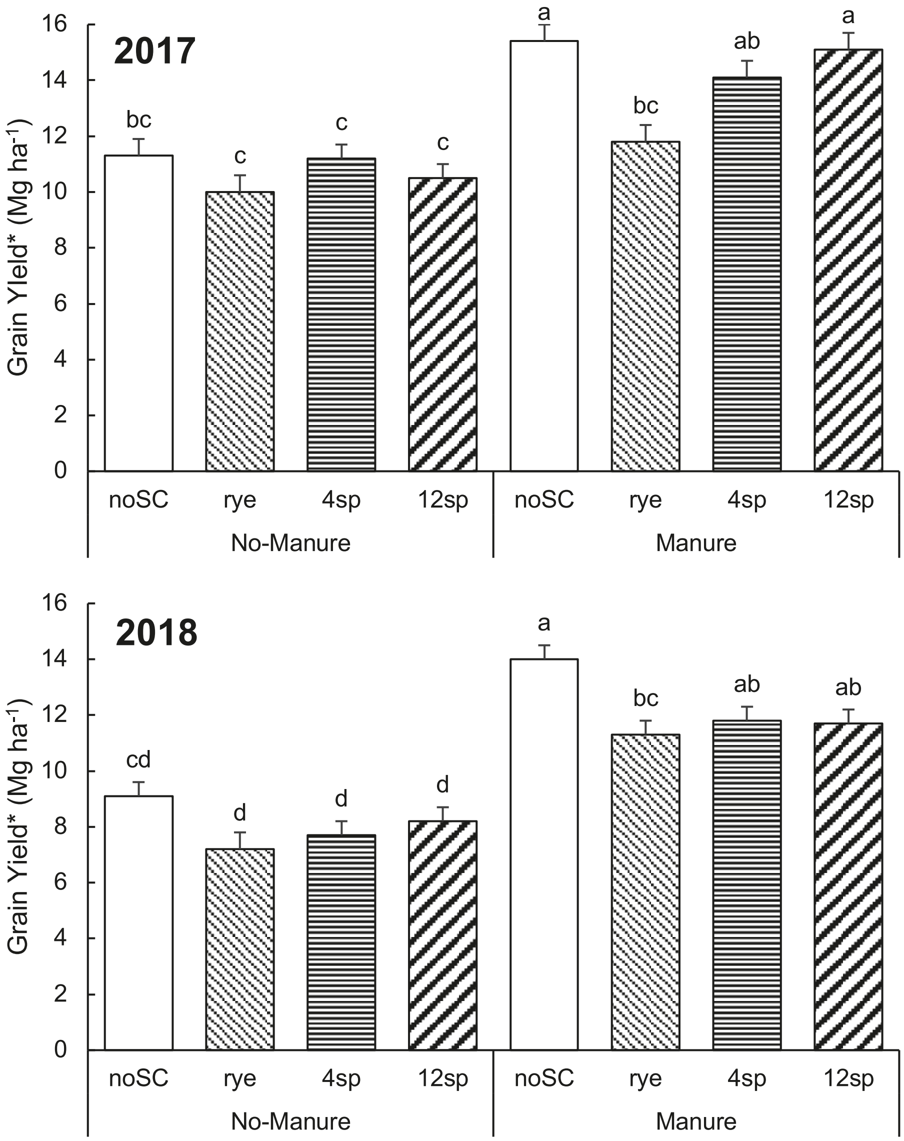


Fig. 4. Final grain yield for the *Year***Manure***SC* interaction in 2017 and 2018. (a–d) Different letters indicate statistical difference according to Tukey–Kramer adjust means comparisons at $\alpha = 0.05$. Abbreviations: rye, cereal rye monoculture; 4sp/12sp, four/twelve species polyculture. *Grain weights are reported at 15% moisture.

seedlings developed, creating the opportunity for a "green bridge" between hosts for pathogens.

While corn populations were not reduced by rye SC treatments in 2017, they were reduced across all rye SC treatments in 2018, where rye had been the dominant species the previous fall. This finding is similar to that of Acharya et al. (2018). The green bridge theory is consistent with reduced populations in 2018 and suggests that stunted corn root growth could have reduced corn N accumulation and yield. In a concurrent experiment, it was found that irrigation eliminated the penalty to corn yield-per-plant following rye (Ogilvie 2019). This makes sense if pathogens impaired root growth and so reduced the ability of corn plants to take up water—supplemental irrigation may have eliminated the negative effect of limited root access. The observations above by Martinez-Feria et al. (2016) and Munawar et al. (1990) also support this assessment.

This study set out to explore the potential for SC polycultures to improve manure N availability to corn relative to a cereal rye SC monoculture or noSC. None of the SCs changed manure N availability for corn, positively or negatively, but rye—which was also present in the polycultures—caused significant reductions in corn population, growth, and yield that could not be attributed to manure N immobilization by rye. Additionally, in year 1, when rye's proportion in the polycultures was reduced, corn yield was not adversely affected following the polycultures; but in year 2, when rye was more dominant in the polycultures, corn population, growth, and grain yield following the polycultures suffered a similar loss to the rye monoculture. It is possible that the effect of rye on corn was caused by root pathogens, which can use both rye and corn as a host, although no root measurements were taken. If SCs are expected to provide ecosystem services, improve crop yields, and be a cost-effective man-

Table 6. Corn grain and stover N accumulation at harvest by SC and SD main effects.

SC	kg ha^{-1}	SE	SD	kg ha^{-1}	SE
		Grain			
noSC	138a	5	noSD	91b	3
rye	106b	4	SD	164a	5
4sp	122a	4			
12sp	125a	4			
		Stover			
noSC	78a	3	noSD	58b	3
rye	68b	3	SD	86a	3
4sp	71ab	3			
12sp	72ab	3			

(a–d) Different letters within a column and parameter indicate statistical difference according to Tukey–Kramer adjust means comparisons at $\alpha = 0.05$.
Abbreviations: SC, service crop; rye, cereal rye monoculture; 4sp/12sp, four/twelve species polyculture; SD, sidedress fertilizer N; SE, standard error.
Note: SC main effect is averaged over manure, SD, sampling times, and experimental years; and SD main effect is averaged over manure, SC, sampling times, and experimental years since other main effects and (or) interactions were not statistically significant.

Table 7. Final corn biomass (dry weight of grain and stover) for the SC main effect.

SC	mg ha^{-1}	SE
noSC	15.9a	0.4
rye	13.3b	0.4
4sp	14.5ab	0.4
12sp	14.6ab	0.4

(a–b) Different letters within a column indicate statistical difference according to Tukey–Kramer adjust means comparisons at $\alpha = 0.05$.
Abbreviations: SC, service crop; rye, cereal rye monoculture; 4sp/12sp, four/twelve species polyculture; SE, standard error.
Note: SC main effect is averaged over manure, sidedress, sampling times, and experimental years since other main effects and (or) interactions were not statistically significant.

agement tool for farmers, then the negative impacts of rye may be mitigated, by planting corn later than 10 days after rye termination (Acharya et al. 2017) and tilling strips such that no living rye roots can touch the roots of emerging corn roots. The risks of rye before corn need to be seriously considered. Another SC species, in monoculture or mixture, may lower the risk to corn production in the following year.

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